

COBRA System Engineering Processes to Achieve SLI Strategic Goals

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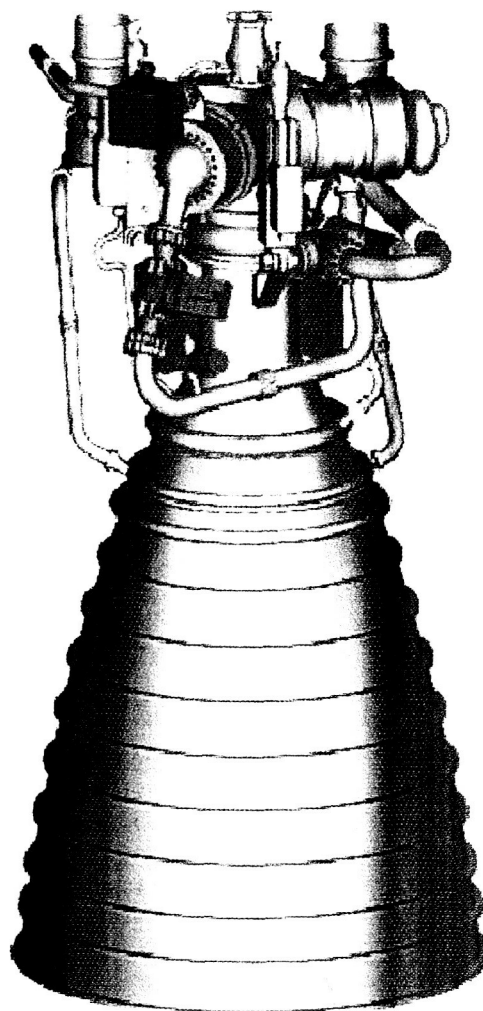
The COBRA Prototype Main Engine Development Project was an endeavor conducted as a joint venture between Pratt & Whitney and Aerojet to conduct risk reduction in LOX/LH₂ main engine technology for the NASA Space Launch Initiative (SLI). During the seventeen months of the project (April 2001 to September 2002), approximately seventy reviews were conducted, beginning with the Engine Systems Requirements Review (SRR) and ending with the Engine Systems Interim Design Review (IDR). This paper discusses some of the system engineering practices used to support the reviews and the overall engine development effort.

1. Introduction

1.1 The Space Launch Initiative

The NASA SLI program was initiated under NRA8-30 to begin development of a space launch system that would be significantly safer and more economical to operate than current launch systems. SLI was identified as part of the Integrated Space Transportation Plan (ISTP) and followed on the NRA8-27 study to define an optimal roadmap that would produce a 2nd-Generation Reusable Launch Vehicle (2GRLV). The objective of the NRA8-27 study was to identify risk reduction areas and were applicable to several 2GRLV architectures by performing cycle analyses and trade studies on applicable propulsion systems. Risk reduction activities were then identified to mature the technologies and cycles to production status. Other elements of the ISTP identified at that time included upgrades for safety of NASA's 1st-generation RLV, the space shuttle, and developing technologies for third and fourth generation transportation systems.

The 2GRLV program was to build on NASA's then-current programs (e.g., X-33, X-34 and X-37) — testing new materials, structures, propulsion, computers and other technologies needed to meet the program's goal of significantly increasing safety to a 1 in 10,000 chance of loss of life and reducing payload launch costs from \$10,000 per pound today to \$1,000 per pound.



The scope of NRA8-30 covered more than just the propulsion facet of space transportation. The ten technology areas (TAs) worked on all elements of the next manned space launch infrastructure. In addition, NRA8-30 was separated into multiple cycles and phases to permit management flexibility. Cycle-1 would focus on initial prototype development and risk reduction, with Cycle-2 culminating in the demonstration by test of the prototype engine. Phase-2 of the SLI program would build on the foundation laid by the prototype engine project by the design, development, test, and deployment of the human-rated full-scale development (FSD) flight engine.

Under Cycle-1 of the 2GRLV program, two prototype LOX/LH₂ main engines were selected for development to reduce technical risks; the COBRA engine by the Joint Venture (JV) of Pratt & Whitney (P&W) and Aerojet, and the RS-83 by Rocketdyne.

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1.2 The COBRA Engine

The Co-Optimized Booster for Reusable Application (COBRA) engine is a reusable, LOX/LH2 600K class engine system utilizing the Single Burner Fuel-Rich Staged Combustion (SBFRSC) power cycle set up around the existing SSME ATD high pressure turbomachinery. The SBFRSC cycle reduces the potential for oxygen-rich failure modes inherent in the dual-burner cycle, thus increasing engine reliability and safety. The hot combustion gases from the preburner drive both the hydrogen and LOX turbines in parallel before entering main chamber. This design decreases the turbine temperature, increasing engine life expectancy. In addition, the use of a single "liquid-liquid" preburner means that the high transient turbine temperatures seen in the dual-burner staged combustion cycle are eliminated. Additionally, the fuel and LOX turbine temperatures are essentially "averaged" in the single-burner system, allowing the peak temperature in the system to stay at a more benign level. The Russian RD-0120 engine also uses this cycle, though with an integrated single-shaft LOX and fuel turbopump.

The COBRA engine system was selected for development under the Cycle-1 of the NRA8-30 SLI program under contract NAS8-01108. The genesis of the COBRA engine system originated during the development of the P&W XLR129 engine for the USAF in the early 1970's. The system utilized a highly integrated "powerduct" arrangement, with the separate turbopumps mounted in a close-coupled configuration with the single fuel-rich preburner to a double-walled hot gas duct. The COBRA prototype engine was to be developed in a step-by-step building block approach that leveraged the heritage of the existing SSME ATD turbomachinery and included extensive testing of subscale, subsystem and prototype hardware.

1.3 Prototype vs. FSD

One of the initial primary objectives of Cycle-1 of the NRA8-30 main propulsion (TA-8) effort was the development of a prototype engine system that "burned down" development risk and cleared the way for development of the FSD flight engine. In the absence of an actual vehicle to drive the FSD engine requirements, a set of prototype (i.e., Level-2) requirements was synthesized from the available vehicle architectures and released in the 2GRLV Propulsion System Requirements Document (PSRD). The JV then generated the system-level (Level-3) requirements from the PSRD and further decomposed requirements to the component level (Level-4) with an emphasis on showing a path (i.e., with little or no development gaps) to the FSD engine. The key requirements were further characterized and tracked by

a Technical Performance Measurement (TPM) process. TPMs are product metrics used in the prototype engine project to detail the development path and track the progress made toward the FSD goals.

The prototype engine components would be of sufficient similarity with the FSD engine to demonstrate functional performance that encompasses the requirements (i.e., flows, temperatures, pressures, transients, self-induced environments, etc.) for the expected FSD engine. Prototype components and component test programs would be designed to induce FSD engine expected loads in areas where technology readiness must be demonstrated. The prototype components would also be of sufficient fidelity to demonstrate functional performance at a level near the FSD engine target to allow validation of analytical design models in the range of expected FSD engine operation. If scaling of the prototype engine design to match actual FSD engine conditions is required following the prototype testing, the analytical models used would be sufficiently anchored to establish the expected trend beyond the prototype test points.

2. Systems Engineering

The development of an advanced propulsion system involves complex requirements, restrictive constraints, the use of sophisticated technologies, and the application of many diverse disciplines and personnel over an extended period of time. *Systems engineering* deals with the development, operation, and expenditure of such a system in an orchestrated manner by identifying and utilizing the interrelationships between elements of the system and the processes by which the system is developed and operated. The application of systems engineering processes is necessary for managing and controlling the development of a rocket engine propulsion system. It describes the process of defining and refining customer requirements into an integrated program and technical plan. Management of the systems engineering processes was detailed in the Systems Engineering Management Plan (SEMP), which also identified the organization, direction, and control mechanisms to insure that program safety, quality, cost, and schedule meet customer expectations.

The JV established an Engine Systems Integration Team (ESIT) which operated in parallel to the Component Integrated Product Teams (CIPTs) and was responsible for system optimization and system trade studies. The ESIT consisted of different elements supporting the system engineering function:

- Systems Design & Component Integration (SD&CI)
- Propulsion Systems Analysis & Integration (PSA&I)

- Product Development & Validation (PD&V)
- Reliability & Mission Assurance (R&MA)
- Manufacturing Systems Engineering (MSE)

2.1 Customer (Government) Insight

The process of customer insight offers many means by which NASA was able to provide input and guidance to the contractor while remaining informed on the progress and current issues of the development effort. This would involve praise and criticism in equal measure, usually cast in both directions. Four levels of insight are currently used at NASA, with Level-1 being the lowest level of government participation (effectively giving the contractor a bag of money and hoping an acceptable product is delivered at the end of the contract period), and Level-4 being the most intensive (the government conducts a similar effort in parallel to the contractor). For the COBRA project, NASA established Level-3 insight, which included:

- regular involvement to identify and resolve issues,
- review assumptions and findings,
- comments to test plans and procedures,
- support resolution of anomalies in test or analysis,
- regular technical interchanges,
- methodical reviews of process analyses and study,
- independent analysis,
- chairing of review boards in a formal fashion with data deliverables commensurate with formal hardware and software development approaches.

2.1.1 Milestone Reviews

One avenue for the provision of customer insight was the conduction of milestone reviews. The COBRA team set a very aggressive development pace in order to

achieve the SLI schedule to demonstrate a Technology Readiness Level (TRL) of 6. In the space of 17 months, the COBRA engine development team successfully conducted about 70 system-, subsystem- and component-level reviews. These reviews included System Requirements Reviews (SRRs), Preliminary Design Reviews (PDRs), Interim Design Reviews (IDRs), Detailed Design Reviews (DDRs) and Critical Design Reviews (CDRs). In addition, there were numerous Technical Interchange Meetings (TIMs) conducted to discuss issues of a particular focus. In the course of the milestone reviews, approximately 525 Review Item Discrepancies (RIDs) were initiated, dispositioned and closed. This number does not include the additional of action items and comments generated during the milestone reviews that were similarly acted on by the JV team. A summary of the different milestone reviews are shown below in Table 1 [1]

Early in the project, it was quickly noted that the high number of reviews was producing a correspondingly large (and seemingly never-ending) number of RIDs. This was due to there being no separation of major issues from trivial ones in the screening of RIDs. The growing problem was that each RID, whether it was critical or irrelevant, had to go through a lengthy process of initiating, screening, dispositioning, implementing, verifying and closing. The formal process of executing RIDs involved an exhaustive chain of signatures that had to be provided at each step in the process (Initiator -> Screening Team Lead -> Developer -> Review Team Lead -> Actionee -> Initiator -> RID Captain -> Lead Systems Engineer -> Project Manager). In addition, if there was a review preboard or board, this also required additional signatures from the chairperson of those entities.

Review →	SRR	PDR	IDR	DDR	CDR
Design Complete (%)	0	50	60	70	90+
Drawings Complete (%)	0	10	15	~35	90+
Primary Review Objectives	<ul style="list-style-type: none"> • Confirm that requirements and their allocations in the system spec are sufficient to meet project objectives 	<ul style="list-style-type: none"> • Demonstrate that preliminary designs meet system requirements with acceptable risk. • Identify all interfaces and verification methodologies 	<ul style="list-style-type: none"> • Confirm that the system, subsystem, and component designs, derived from the preliminary design, are of sufficient detail to allow for orderly hardware / software design status assessment and smooth transition towards the manufacturing phase. 	<ul style="list-style-type: none"> • Same as the IDR, only serves as an additional check on the engine development progress. 	<ul style="list-style-type: none"> • Confirm that the system, subsystem, and component designs, derived from the preliminary design, are of sufficient detail to allow for orderly hardware/software manufacturing, integration, and testing, and represent acceptable risk.

Table 1: Milestone Reviews

Finally, the COBRA Project Manager decreed that all RIDs had to be closed prior to the successive review as part of the entrance criteria. All this collectively generated a scenario of programmatic disaster if the discrepancy process was not streamlined.

In order to effectively conduct the high volume of reviews, they were separated into either primary (government-led) and secondary (contractor-led) reviews. The difference between primary and secondary reviews focused primarily on the scope of the review and processes used to document and correct discrepancies. The scope of primary reviews was primarily on system or subsystem level design, while secondary reviews focused more on the component level. Primary reviews used a modified RID process to document and correct discrepancies, and the secondary reviews use a less formal Action Item process. Secondary reviews also did not require the convening of a review preboard or board.

For a primary review, in addition to RIDs, Action Items and Comments were also be used to document discrepancies of less gravity. Action Items were provided to the contractor to evaluate for correction external to the RID process and were dispositioned, tracked and closed by the contractor with the concurrence of the initiator (thereby reducing the signature cycle from 9+ to 2). The criteria for classifying discrepancies as Action Items are:

- Discrepancies that do not require NASA oversight to implement a corrective action and do not have a cost or schedule impact that must be supported by NASA (i.e., the corrective action is necessary but external to the current negotiated scope of work). An Action Item can have a cost or schedule impact if the contractor accepts that the corrective action is within the current scope of work.

- Discrepancies that are not within the immediate scope of the review, but are relevant to be considered for the longer-term goals.

Closure and tracking of RIDs were still controlled by the government, while Action Items were controlled by the JV with government insight into their status. Discrepancies classified as Comments are those that are considered to be of a non-critical nature and whose corrective action is left to the discretion of the Contractor. The closure of Comments is not tracked following its delivery to the contractor.

Another practice that was implemented as part of the review process was the use of periodic "RID closure summits" that were used to assess the closure status of RIDs and Action Items leading up to the entry gate meeting of a particular review. This was useful in preventing a last-minute feeding frenzy of RID closures on the days before the entry gate meeting and also helped to ensure steady progress in the correction and closure of all discrepancies.

2.1.2 IPT Participation

Another important avenue of providing insight to the contractor was the participation in the regular standing IPT meetings to status component development. To effectively support these meetings, programmatic and institutional government personnel would attend to help resolve any issues that might arise. This permitted regular involvement to assist in the identification and resolution of issues or anomalies, review analysis findings or their guiding assumptions, and provide a regular source of technical interchange.

Also, in order to promote better communication between the customer and the contractor, the NASA COBRA Project Office structured its personnel in parallel to the JV organization. This is shown below in figure 1 [2]:

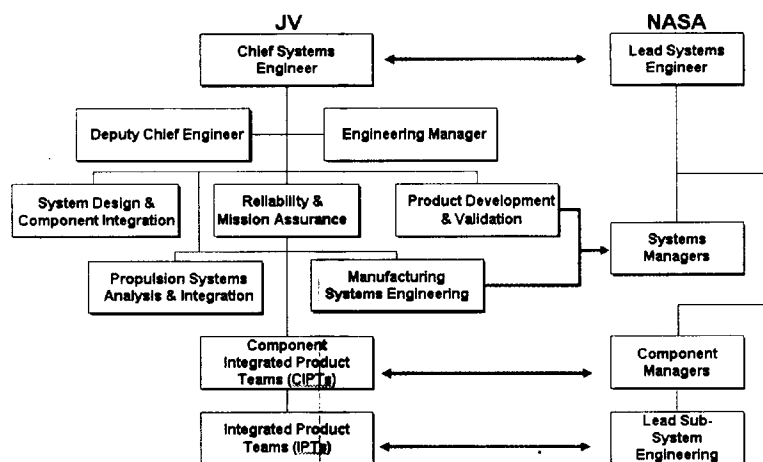


Figure 1: COBRA Organizational Structure

2.1.3 Data Deliverables and OPRs

Another source of customer insight external to the milestone reviews was the periodic submittal of data deliverables that reported the development progress and documented the results of analyses and trades. Each submitted document was written in accordance with the Data Requirements Description (DRD), which were collected in the Data Procurement Document (DPD). Each DRD was assigned to an Office of Primary Responsibility (OPR), who was a government person charged with the responsibility to ensure that the document submitted was 1) of satisfactory quality, 2) in compliance with the DRD, 3) submitted on time, and 4) showed steady progress in the development of the engine toward the project goals.

During the course of the COBRA project, over 500 documents were officially submitted to the government, many of them resubmittals or updates of previously-submitted documents. This heavy load of documentation was a significant strain on the OPRs, which generated an increased risk of losing or degrading the insight offered by the documents. It was also a burden on the contractor, who had to draft the documents in the first place. Finally, it was clear that a document that was not given sufficient review by the customer was a waste of time and money.

The process for the preparation, delivery and review of the data deliverable documents was extensively (and repeatedly) revised over the course of the project, with the objective being to orchestrate the content and delivery frequency of the documents to where the OPRs were not overwhelmed. This problem can be avoided in future projects by careful selection and wording of the DRD at the beginning of the project, preferably during contract negotiations.

2.2 The Design Cycle

A *design cycle* is the interval between major engine-level milestone reviews. During this period, there should be one or more iterations of the engine system design to:

- Update system-level requirements and verification criteria/plans, which were flowed down to the component level using the Dynamic Object Oriented Requirement System (DOORS) database. DOORS was also used for verification planning and compliance tracking.
- Incorporate the latest component configurations and intra-engine interface definitions into the systems models using the Component Interface Control Records (CICR) database system.
- Perform the required system level analyses (loads, power balance, FMEA, etc.) with the most current

component configurations based on the CICR inventory.

- Flow the system level analyses results to the components and subsequently assess component compliance with the system analyses.
- Revise all drawings and intra-engine interface definitions to reflect the updated analyses.

The establishment of an effective design cycle requires the orchestration of the data flow and phasing to facilitate proper horizontal and vertical alignment of the engine design maturity at the end of the design cycle. Absence of a rigorous systems engineering process for regulating the design cycle will ensure that engine development follows the less-efficient "tossed salad" design cycle approach which is less likely to provide horizontal and vertical alignment of the engine design state at the successive engine-level milestone review.

Proper vertical and horizontal integration requires that all teams (IPTs, SD&CI, PD&V, R&MA, PSA&I, MSE, ESIT, CCB, and perhaps RMT) work as an integrated team, orchestrated mostly by the Chief Engineer and/or SD&CI, through a design cycle. The engine development plan should explain what data is needed first and why, and then what is needed next, and so forth through the end of the design cycle.

2.2.1 Data Flow and Phasing

SE team planned the data phasing used to accomplish a design cycle, including data outputs and inputs for design and analysis activities. The phased logic used took data outputs (analyses, design trades and drawings, etc) from a work item conducted earlier in the design cycle, and input this data into another work item that required a finite time to be completed during the design cycle.

2.2.2 Horizontal Alignment

Horizontal alignment of the engine system assures that all associated system documentation (i.e., requirements, interface definitions, power balance or loads model version, etc.) is consistent such that the design presented at the milestone is traceable to the system requirements and has been analyzed at the system level to show compliance with the system level requirements. This is to guarantee that there are no discontinuities in the data or design used in the engine design at the time of the milestone review.

2.2.3 Vertical Alignment

Proper orchestration of the *vertical alignment* of the engine development assures that all components at the time of a milestone engine review milestones are at a maturity level greater or equal to the engine milestone as indicated by the completion of component milestones. For example, at the time of the prototype

engine system IDR, all constituent components had at least to have successfully completed their component level IDR.

2.3 Fusing SLI Strategic Goals (the 'ilities) into the COBRA

One thing that was made clear early and repeatedly in the COBRA project was that the engine had to do more than efficiently produce thrust – it had to be markedly safer, more reliable and more cost effective than any rocket engine before it. One important Lesson Learned that was emphasized was to make the engine safe, reliable and easy to maintain as key features of the initial design and avoid correcting safety issues by the application of labor-intensive and costly maintenance and operations “band-aids.”

To accomplish this, both partners of the JV brought their own unique strengths to the table. In addition to a long heritage in the development of rocket engines, P&W also has even more experience in the development and deployment of highly reliable commercial and military turbine engines. While there is no direct relationship between liquid rocket engines and turbojets, there was an obvious benefit in utilizing some of the design approaches used in the turbine engines that would enhance the safety, reliability, and maintainability of the COBRA. At the same time, Aerojet had its own unique history of solid and liquid rocket engine development, most specifically in the area of combustion devices. In addition to a growing experience base in the development of channel-wall nozzles and combustion chambers, Aerojet would also be contributing its talents in the use of platelet injectors for the preburner and main injector, which had a long history of trouble-free use on the AJ10-190 OMS engines on the Space Shuttle.

However, to produce the COBRA to where it achieved the strategic program objectives would require more than a proven track record with demonstrated technologies, it would require the right development approach to make certain that “the ‘ilities” were given the right amount of up-front emphasis in the engine design and not shoe-horned in later as an afterthought.

2.3.1 IPT Staffing and Empowerment

To help ensure that enough consideration was given to the strategic objectives of the development project, the JV made sure that the Integrated Product Teams (IPTs) for all components had representatives from ESIT, especially the R&MA element.

Each design cycle involved a review of the component failure modes, projected maintenance activities and the time and manpower required to accomplish it. Any change to a component design required consideration

the change would have on adjacent components, the engine system, and the TPMs. It was emphasized that at a level of maturity that enabled a design-to-safety approach, the FMEA had to be maintained in a timely way to affect trades and planning for controlling safety-critical items via inspections.

2.3.2 Decomposition & Allocation of Key Requirements to the Component Level

An important facet of the systems engineering function is the decomposition, flow-down and traceability of requirements to the component-, and possibly subscale-, level. This can typically include requirements such as weight and cost. Specific to the COBRA development effort, this also included the unique decomposition and allocation of reliability and turn-around-time (TAT) requirements to the component level. The decomposition of these requirements to the component level would collectively achieve the project-critical system-level requirements.

2.3.3 TPM Tracking

TPMs are the key goals of the 2GRLV main propulsion system program explicitly defined as product metrics. Target TPMs for the COBRA FSD engine were defined early in the prototype engine development project after a careful examination of the PSRD and consideration of the competitive goals of the JV. TPMs for the prototype engine development project were then defined based on the FSD engine TPMs, and the level of achievement to be accomplished during prototype engine development to show the path to the FSD TPMs. The prototype engine TPMs became the key criteria by which success of the prototype development was determined and was reported on a monthly basis. TPMs monitored for the COBRA engine included:

- Safety & Reliability
- Weight (& Thrust/Weight)
- Performance
- Cost (Cost/Engine/Flight, DDT&E Cost)
- Engine Life
- Maintainability (overhaul interval, TAT, LRU or engine replacement time)

In the event that a TPM was noncompliant with its allocated metric or indicated increased evidence of development risk, a risk item was initiated in the engine risk database for tracking and mitigation. A risk mitigation plan would be worked out that would be executed to bring the TPM into compliance with the 2GRLV objectives. In some instances, this might involve trading of trading TPM allocations at the component level with components with surplus allocation margin. In other cases, it might require a redesign effort to resolve the noncompliance.

2.3.4 Trade Weighting

In addition to the foundation laid by the work conducted under NRA8-27, innumerable trade studies were performed during the conceptual and preliminary design phases of the engine development. Any trade, which impacted more than one IPT was considered a system level trade. System level trades assured that the engine system was optimized, not necessarily to any one component. These trades identified engine characteristics such as the powerduct shape, pump orientation, and gimbal mount attach points. The final types of trades conducted were component trades. These trades were to performed ensure that all allocated requirements are met by all components, thus ensuring all system level requirements are met.

The 2GRLV program TPMs were organized into four major groups which represent the major figures of merit to be used in the evaluation of the trade. In rank of highest weight, they were:

- Safety & Reliability
- Economics & Cost
- Technical Performance
- Risk Reduction.

The Safety & Reliability figure of merit was further decomposed into Loss of Crew/Vehicle, and Launch Availability. The Economics/Cost figure of merit is broken down into Development Cost, Production Cost, Operations Cost, and Launch Cost. All of the objectives had corresponding engine attributes associated with them, each of which is given a numerical score.

3. Summary

Shortly before the engine-level milestone IDR in the summer of 2002, NASA announced that it would not exercise the contract option to continue development of the COBRA engine. This fate also befell the Rocketdyne RS-83 engine development project. The suspension of development efforts was not due to technical or programmatic deficiencies in either project, but was due to reorientation of SLI priorities to focus on LOX/kerosene booster engine development. With

the limited program budget (and manpower), the LOX/LH2 development effort could not be continued in parallel and was suspended.

As an epilogue, in the spring of 2003, the NASA Office of Aerospace Technology (OAT) awarded the COBRA project an award for "Turning Goals into Reality" in recognition of their accomplishments. The award statement reads as follows:

COBRA - An example of technological innovation and exemplary teamwork

Liquid oxygen/hydrogen single-preburner-fuel-rich-staged-combustion engine scaleable from 200k-1000k lbf with prototype design at 565klbf utilizing a GOX-driven boost pump, SSME pump technology, liquid-liquid preburner, platelets, channel-wall nozzle, and health management providing a factor of 50 safety and 10 life than current world benchmark. Developed with a strategy of insight and teamwork between NASA/MSFC and Pratt & Whitney/Aerojet to design a prototype with risk reduction of enabling technologies for a new generation propulsion system using Space Shuttle lessons lived and innovative business practices through rigorous risk management with strict adherence to Earned Value and Systems Engineering.

It should be emphasized that this paper is not intended to describe the entire end-to-end systems engineering process that was utilized during the COBRA development effort, only those techniques that were developed by the JV and its NASA insight counterparts to help ensure that the resulting product was a demonstrably safe, reliable and cost-effective prototype engine that could be efficiently carried forward into the FSD effort. The development of these techniques was by no means instantaneous or painless, but in the end showed a high degree of synergy in orchestrating the efforts of so many talented personnel toward a common goal.



BIBLIOGRAPHY

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² Private communication from COBRA Project Manager, James Snoddy, 8 Jul 03